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# Dynamic Skew Measurements in 7, 19 and 22-core Multi Core Fibers

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**Abstract:** We report simultaneous dynamic inter-core skew measurements between 7 cores of several homogeneous MCFs. The largest variation was 4.33 picoseconds for 31km span with diminishing influence of mechanical vibrations, temperature, core-layout and wavelength observed.

**Keywords:** multi-core fibers; dynamic skew; transmission; space division multiplexing; optical communications

## I. INTRODUCTION

Optical networks and communications systems are a key part of the global communications infrastructure, underpinning the digital economy, supporting intensive data communication needs of industry, commerce, academic institutions, governments and individuals worldwide. However, the current optical communication infrastructure is constantly challenged by the soaring traffic demands dictated by the modern Internet of Things (IoT) trends, “Big Data” establishment, intense social networking and high definition (HD) content transferring. Space-division-multiplexing (SDM) technologies [1] and networking approaches [2] have widely been proposed to enable cost-effective large scale capacity increase in transmission capacity with multiple fiber cores [3] or spatial modes [4] being used to increase the number of transmission channels in a single fiber. In particular, homogeneous single-mode (SM) multi-core fibers (MCFs) offer a good opportunity for adoption of high-capacity SDM technology in the near term having been shown to support high spectral efficiency (SE) modulation formats and wide band operation without the complexity of high-order multiple input-multiple output (MIMO) based receivers [3]. They can also be fabricated with relatively low SDM-crosstalk (XT) and a smaller core diameter than equivalent FM-MCFs, making splicing and handling easier [5]. Furthermore, the relative uniformity of cores in SM-MCFs with homogeneous cores supports spatial super channels (SSCs) for shared, transmitter hardware, DSP resources and simplified switching [6]. SSCs are also compatible with other system features relying on correlated propagation delay such as self-homodyne detection with pilot-tone transmission [7] or multi-dimensional modulation or coding [8] across cores.

However, the success of such systems depends to some extent on the magnitude of variation in propagation delay between signals travelling in different cores. As has been an issue for parallel datalinks since the introduction of electronic parallel transfer buses, this dynamic inter-core skew has implications for achievable baud-rates, transmission distances, receiver design and complexity of digital signal processing (DSP). Hence, characterizing it over extended time periods is crucial to fully understand the usefulness of such systems. Previously, the inter-core skew in MCFs was investigated by considering the skew between core pairs in a single 7-core MCF [10]. Here, we use a novel experimental set-up to extend that study and simultaneously measure dynamic inter-core skew of all cores of a 7 core fiber as well and apply the same set-up to investigate the skew in multiple cores of high core count MCFs with 3 ring structures for the first time. With fibers up to 22 cores, we observe that dynamic skew fluctuations can be caused by vibrations and temperature changes with lower dependence on core layout, fiber design and even smaller impact of wavelength observed.

## II. EXPERIMENTAL DESCRIPTION

The experimental set-up for simultaneously measuring skew fluctuation between multiple cores is shown in Fig. 1.

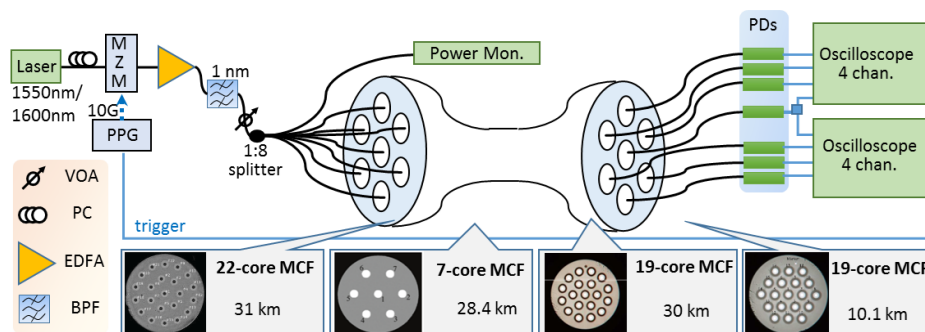


Fig. 1. Experimental set-up for dynamic skew measurements. Insets: the studied MCF

On the transmitter side, the light source was a C/L-band tunable external cavity laser (ECL), modulated by a Mach-Zehnder modulator (MZM) driven by a pulse pattern generator (PPG) at 10Gb/s. The modulation format on-off keying (OOK) using a  $2^7-1$  pseudo random binary sequence (PRBS). The generated signal was amplified by an erbium-doped fiber amplifier (EDFA) and then filtered by a 1 nm band-pass filter (BPF) to limit the amplified spontaneous emission (ASE) noise bandwidth. Next, a variable optical attenuator (VOA) was used to control input power before dividing in a 1 x 8 power splitter. Seven copies of the same signal were injected in seven different cores of the MCF while the eighth output of the splitter was used to monitor the injected power to the fiber. The injected power was maintained between 4 and 6 dBm depending on the fiber and their losses with 3 fibers using 3D waveguides to couple light in MCF cores with the exception being the 30 km 19-core fiber which used free-space couplers.

After fiber transmission, the signals were received by seven individual 10G photodetectors (PDs). The resulting electrical signals were sent to two identical high sampling rate oscilloscopes, each equipped with four 33 GHz channels. In order for the oscilloscopes to have a common reference, the electrical signal from the center core's PIN, was electrically split and fed to both scopes which were both triggered by a pattern synchronisation signal from the PPG. The relative dynamic skew between each core and centre core was estimated by cross-correlating the corresponding cores, as in [9]. The homogeneous MCFs that were studied here, comprised various designs and characteristics, including core arrangement design, core pitch, core number, etc. As a result, the cores under test were carefully picked for each fiber, in order to explore any possible effects from the above-mentioned diversities. The fibers' detailed specs along with references are shown in Table I with facet photos shown as inset in Fig. 1.

TABLE I  
MULTI CORE FIBER SPECS

MCF type	Length (km)	Average Insertion Loss (dB/km)	Core pitch (um)	Cladding diameter (um)	Core arrangement	Ref.
7-core	28.4 km	0.184	44.2	160	hexagonal	[9]
19-core	10.1 km	0.227	35	200	hexagonal	[10]
19-core	30 km	0.285	39 & 37,6	220	circular	[11]
22-core	31 km	0.2	41 & 48	260	circular	[3]

### III. RESULTS AND DISCUSSION

Skew fluctuations were observed for a period of 18 hours along with temperature monitoring. Fig. 2 depicts the resulting dynamic skew plots along with the rate of change ( $dSkew/dt$ ) of those skew variations obtained for the fibers under analysis. The various core layouts with core numbering and colors matching the plot lines are also included as insets. The center core (no. 1) was used as a reference core to which the relative dynamic skew of the rest of the selected cores was measured. The skew between core  $n$  and  $m$  is symbolized as  $n-m$  and is represented by the color of each core. Fig. 2-a and Fig. 2-b show the evolution of dynamic skew for the 7-core MCF firstly with the laser tuned in 1550 nm and then in 1600 nm. In both cases, the maximum skew fluctuation was observed in the 1-5 core pair with values of 2.3 and 3.7 ps respectively. Although greater skew fluctuations was observed for the longer wavelength case, considering the statistical fluctuations and influence of external factors discussed below, there is not strong evidence for a wavelength dependence of dynamic skew variation. Indeed, as discussed below, the abrupt change in measured dynamic skews for all cores after 8 hours in Fig. 2-a was most likely caused by mechanical vibrations.

Over all the measurements, both vibrations and temperature appear to influence the measured skew values. Measurements of the ambient lab temperature show that it was varied by only two degrees over all measurement period but the frequency of the temperature fluctuations appear to have some correlation with the measured fiber skew. This is most evident in Fig 2-c and Fig. 2-d, showing the data for the 19-core fibers; although we note that the reduced length of the 10.1 km fiber could also be a factor for reduced skew fluctuations, since longer spans are more likely to be affected by temperature, vibrations or fiber imperfections. This fiber exhibited a maximum skew fluctuation of 0.79 ps for the 1-17 core pair with a reduced dynamic skew fluctuation rate which is just 0.002 ps/s for the same cores.

The impact of vibrations on inter-core skew is best observed in the results from the 22-core MCF, in Fig. 2-e, which show that measurements taken in periods with the least activity and resulting sources of mechanical vibrations, such as the early hours of morning (between 9 to 15 elapsed hours), result in less dynamic skew fluctuations compared with daytime measurements. In contrast to the other fibers mounted on isolated optical benches, this fiber was mounted on a trolley with the least mechanical isolation and positioned close to the main lab door. The above fact and the resulting movement of people and equipment in close proximity to the fiber and mechanical vibrations from door closing were observed to cause large step changes in the measured skew. Indeed, the largest of all measured skew values was with this fiber, being 4.33 ps with 0.0178 ps/s  $dSkew/dt$  for the 1-2 core pair.

Over all plots, although the cores with the largest dynamic skew variations tend to be outer cores, suggesting that higher skew is more likely for cores with larger physical separation, the effect is not constantly apparent to allow firm conclusions of this point.

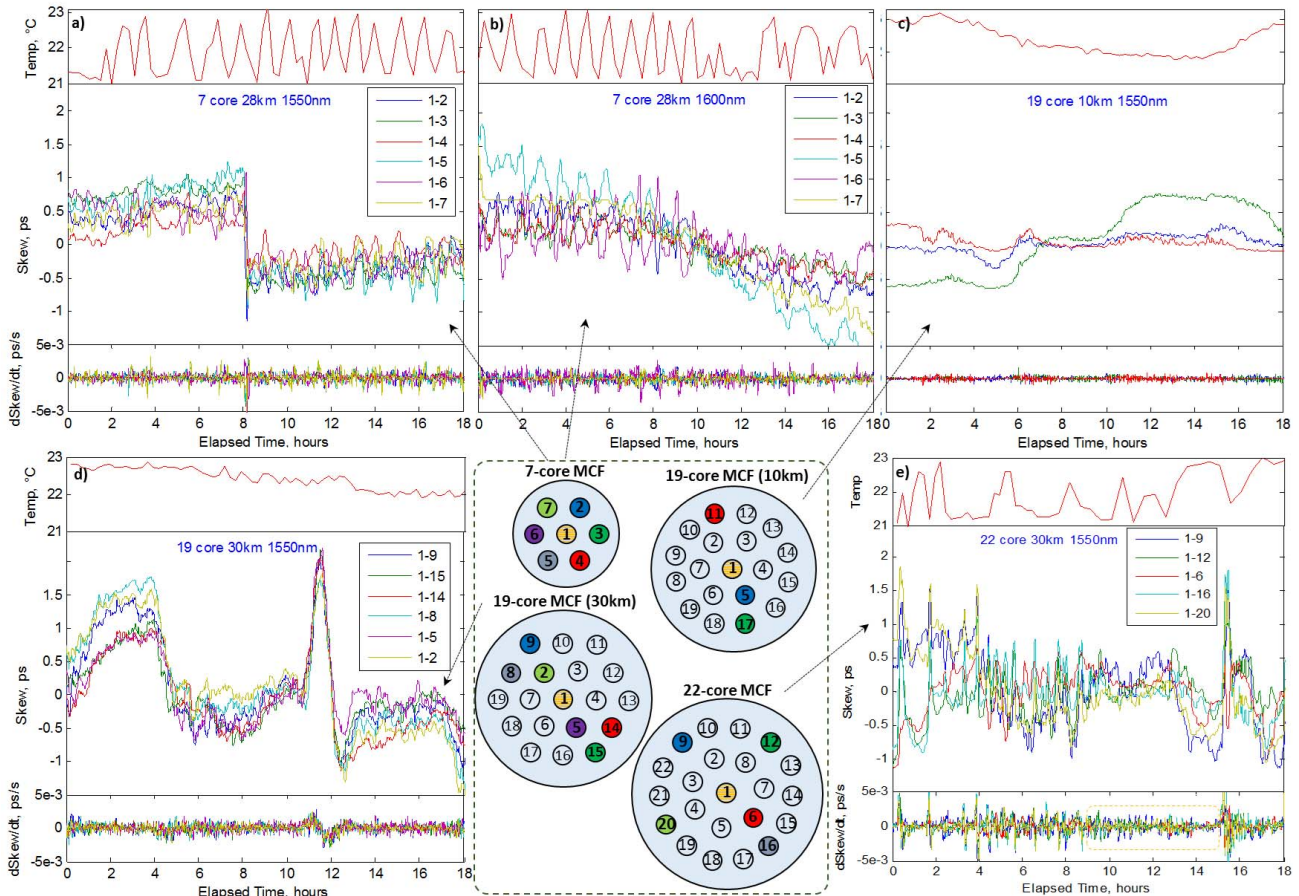


Fig. 2. Dynamic skew (ps) and its evolution rate (psec/sec) measurements for the MCFs under test with the associated temperature over a period of 18 hours. Insets: the selected cores for each skew measurement.

#### IV. CONCLUSION

We have investigated the dynamic inter-core skew in high-core count MCFs with three different core layouts and simultaneously in all cores of a 7-core fiber. We observed that, although skew is often larger in the outer ring cores than in the inner ones, it mostly appears to become more prone to mechanical vibrations and temperature changes.

#### ACKNOWLEDGMENTS

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